HIGH PRECISION AND REAL TIME TRACKING OF LOW EARTH ORBITERS WITH GPS: CASE STUDIES WITH TOPEX/POSEIDON AND EUVE

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Abstract

Methods of GPS-based orbit determination have been tested on two low earth orbiters, TOPEX/POSEIDON and EUVE. TOPEX/POSEIDON carries a dual-frequency 6 channel GPS receiver while EUVE has a 12 channel single frequency receiver.

Flying at an altitude. of 1334 km, TOPEX/POSEIDON performs precise ocean altimetry, which demands the highest possible accuracy in determining the radial orbit component in post-processing. Radial RMS accuracies of' about 2 cm were realized using reduced dynamic tracking techniques. In this approach, orbit errors due to force arc substantially reduced by exploiting the geometric strength of GPS to solve for a set of stochastic forces.

On EUVE, the emphasis was on evaluating real time positioning techniques with a single frequency receiver. The capability for real time 3D accuracies of 15 m in the presence of Selective Availability was shown. This was validated by comparing to a post-processed differential GPS truth orbit believed accurate to about 1 m.

1. Introduction

1.1 TOPEX/POSEIDON, GPS POD

In the mid- 1980s the TOPEX/POSEIDON project agreed to develop and fly an experimental Global Positioning System receiver to test the ability of GPS to provide precise orbit determination (POD) by an unconventional new technique [*Melbourne et al.,* 1994; *Bertiger et al.,* 1994]. The GPS Demonstration Receiver (GPSDR), an early version of the Motorola Monarch™, tracks up to six GPS satellites concurrently, measuring the phase of the *L1* and *L2* carrier at 1-sec intervals and pseudorange at 10-sec intervals. Measurement noise on the ionosphere-free observables, including instrumental thermal noise and multipath effects, is about 5 mm for phase and 70 cm for pseudorange. If the orbits and clock offsets of the GPS satellites are known (they are broadcast by the GPS satellites) the receiver can determine its position and time (four unknowns) geometrically (within the errors of the broadcast data) at any instant with data from only four satellites. It is this extraordinary geometric strength that distinguishes GPS as a tracking system. Such ground-based systems as SLR (satellite laser ranging) and DORIS (Doppler orbitography and radio positioning integrated by satellite) typically provide measurements in just one direction at a time and may have substantial coverage gaps; they must therefore rely on models of satellite trajectories (derived from models of the forces acting on the satellite) to recover three-dimensional information.

With a technique known as reduced dynamic tracking [*Wu et al.*, *1991*; *Yunck et al.*, 1990] we can exploit the 3D geometric strength of GPS to minimize dependence on dynamic models and, in theory, achieve a superior orbit solution through an optimal synthesis of dynamic and geometric information. A variation on that technique called kinematic tracking can yield a precise solution almost entirely by geometric means with a sufficiently capable GPS receiver.

Conventional dynamic POD depends on precise models of the forces acting on the satellite to describe the trajectory. In a dynamic solution the estimated parameters will typically include the satellite initial state (position and velocity) and a few quantities describing the force models (e.g., a drag coefficient and once-per-revolution empirical accelerations). These are adjusted to yield a solution that best fits the observations, but that solution will necessarily have errors arising from errors in the force models. With GPS tracking, the model errors can be observed in the 3-D residuals between the orbit solution and the observations. This residual information can then be applied in a point-by-point geometric adjustment of the satellite position to give the reduced dynamic solution. Reduced dynamic tracking is implemented in the GIPSY-OASIS II software [*Wu et al.*, 1990; *Bertiger et al.*, 1989; *Webb et al.*, 1993] by solving for a set of stochastic acceleration parameters. By adjusting the time correlation and steady state standard deviation (σ) of these parameters, the optimal solution may be obtained. Differences between dynamic and reduced dynamic solutions can expose the model errors and allow us to study their geographical and spectral distribution and to improve the dynamic model. For example, the GPS data were used to improve the gravity model used in TOPEX/POSEIDON data processing (JGM-3 gravity field, [*Tapley et al.*, 1994]).

Of course, with GPS reduced dynamic tracking of TOPEX/POSEIDON, there are errors due to GPS clocks and orbits. in order to minimize these errors, the GPS signals are observed not onl y on-board TOPEX/POSEIDON, but also at a set of 12.-16 ground receivers well distributed over the earth, Fig. 1. Errors in the GPS constellation are minimized in the solution by a simultaneous adjustment of TOPEX/POSEIDON and GPS orbi 1 parameters, and ground stat i on parameters. Data from TOPEX/POSEIDON improves the knowledge of GPS orbits.

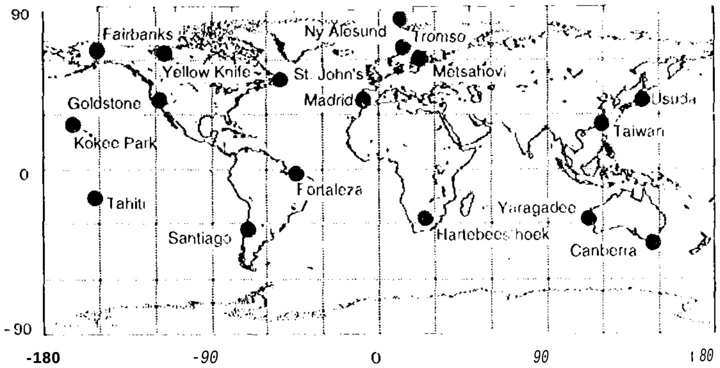

Figure 1. GPS global tracking network

The GPS-determined TOPEX/POSEIDON orbits have a radial RMS accuracy Of about 2 cm with along track and cross track component errors of about 5 cm RMS.

1.2 *EUVE Real Time OD*

The Extreme Ultra violet Explorer (EUVE) was launched in June of 1992 at an altitude of about 500 km. Its mission is to survey the sky in the extreme ultraviolet [*Bowyer*, 1994]. Motorola donated the engineering version of the TOPEX/POSEIDON GPS receiver, modified to perform as a single frequency 12-channel receiver, to be flown as an experiment on EUVE. The receiver was adapted to the spacecraft's requirement to rotate continuously. Thus EUVE is equipped with two oppositely directed antennas to assure good GPS reception at all times. There are two disadvantages to the antenna/receiver arrangement over that of TOPEX/POSEIDON. Single-frequency introduces ionospheric errors in the EUVE GPS data. The EUVE antennas are small patches located on the spacecraft body, increasing the multipath errors over those with the choke-ring antenna on TOPEX/POSEIDON located on a 4.3 m boom.

The goal of the GPS experiment was to evaluate the potential real time positioning performance of a single frequency GPS receiver. The receiver currently performs a position solution on-board every 10 seconds using pseudorange data from 6 GPS satellites through a least square fit, without employing dynamical models or the previous states of the spacecraft. These cm-board positioning solutions are dominated ‘ by Selective Availability (SA) errors and have an RMS accuracy of about 50 m. Other real time positioning algorithms were evaluated by processing the raw data on the ground in a manner that would be consistent with real time processing of GPS data on-board the spacecraft. The optimal on-board solution uses selected terms of the earth's gravity field to faithfully represent EUVE dynamics. The use of dynamical information would allow real time solutions with 3D RMS errors of 15 m in the presence of SA [Gold *et al.*, 1994; *Gold*, 1994]. Since no precise truth orbit was available for EUVE, a precise differential GPS orbit was constructed with a 3D RM S accuracy of about J m [*Gold et al.*, 1 **994].**

2. TOPEX/POSEIDON 1'01) Processing

J]'] .'s GIPSY-OASIS 11 software was used to analyze the GPS data. As part of the orbital accuracy assessment comparisons were made to TOPEX/POSEIDON orbits produced with SLR and DORIS data using two other software systems, UTOPIA, developed by University of Texas Center for Space Research (CSR), and GEODYN, developed by the Goddard Space Flight Center (GSFC). GEODYN is used to produce the official orbits released to the science community along with the altimeter data. The GIPSY/OASIS 11 solution proceeds in two stages. First, a standard dynamic solution is performed. This is then used as the nominal orbit from which the final reduced dynamic orbit is determined. With GIPSY/OASIS II, data are fit in 30-hr batches centered on noon UTC. This results in a 6-hr overlap between consecutive days. "l'he RMS difference during the 6-hr overlap period may be used as a measure of orbit precision.

2.1 *Dynamic Models*

While the analysis systems share common dynamic models, those models are realized through implementations which give slight differences in the computed ocean tides and earth albedo. All solutions use the Joint Gravity Model-2 (JGM-2) gravity field tuned with TOPEX/POSEIDON SLR and DORIS data [*Nerem et al.*, 1994] or Joint Gravity Model-3 (JGM-3) [*Tapley et al.*, J 994] which was tuned with four 1 ()-day cycles of TOPEX/POSEIDON GPS data. A custom model for the solar and thermal radiation forces on TOPEX/POSEIDON was developed for the SLR/DORIS effort [*Marshal et al.*, 1992]. These small, slowly varying dynamic model differences can be largely accommodated through the adjustment of an empirical acceleration parameter, $\vec{a}$, of the form

$$\vec{a} = \vec{C} + \sum_{i=1}^{2} \vec{A}_i \cos \omega_i t + \vec{B}_i \sin \omega_i t \tag{1}$$

where $\vec{C}, \vec{A}_i$, and $\vec{B}_i$ are constant vectors in the spacecraft coordinate system oriented in the nominal along-track and cross-track directions. The frequencies ω_i are once- and twice-per-revolution of TOPEX/POSEIDON and t is time past an epoch. Solutions produced by CSR (with UTOPIA) and GSFC (with GEODYN) adjusted constant and once-per-revolution along-track and cross-track amplitudes, while JPL's preliminary dynamic adjusted twice-per-revolution terms in those components as well. Empirical once- or twice-per-revolution radial terms are not adjusted because of their high correlation with the along track coefficients.

2.2 *Reduced Dynamics*

The principal practical difference between the software systems is the ability of GIPSY/OASIS II to treat any parameter stochastically. Stochastic estimation of the amplitudes ($\vec{C}, \vec{A}_1, \vec{B}_1$) in eq. 1 is used to produce the reduced dynamic solutions.

Initially, when the best available gravity model was JGM-2, only the constant term, $\vec{C}$, was treated stochastically. With JGM-3 it was found that treating, the once-per-rev coefficients stochastically improved the solution. Tuning of the stochastic constraints with JGM-3 was performed by comparing orbits using altimeter crossover statistics (discussed below). The altimeter crossover software was not available for the initial tuning with JGM-2, which was performed by minimizing the orbit overlap differences from consecutive data arcs. For the orbits determined with JGM-2, process noise accelerations are modeled as first-order Gauss-Markov (colored noise) processes with a correlation time of 15 min and steady state sigmas of 10, 20, and 20 nm/s² in the radial, cross- and along-track directions.

The JGM-3 dynamical orbits (no stochastic accelerations) were as good as or slightly better than the previous reduced dynamic orbits. The reduced dynamic orbit had to be retuned for this improved dynamic model. By comparing altimeter crossover statistics, it was determined that constraining the arbitrary stochastic accelerations to 1 nm/s² in all components with a 15 min time correlation while allowing the once-per-rev empirical acceleration terms to be stochastic gave the. best orbits. Empirical once-per-rev accelerations arc more tightly coupled to the dynamics than the arbitrary constant accelerations. The amplitudes in the cross and along track directions are adjusted with a steady state sigma of 5 nm/s^2 and a correlation t imc of about 3 revs (3x 112.5 rein).

2.3 Additional GIPSY/OASIS II Adjusted Parameters

In addition to the TOPEX/POSEIDON dynamic and reduced dynamic parameters a number of other parameters arc adjusted in the solution process. These include zenith tropospheric delays, GPS states and solar pressure parameters, carrier phase biases, and GPS and station receiver clocks. Reduced dynamic orbits based on the dynamic orbits must be tuned based on the dynamic models used.

3. TOPEX/POSEIDON Orbit Accuracy and Precision

Postfit residuals. As part of the automated quality control, the software examines postfit phase and pseudorange residuals over the full arc. Anomalous data points arc automatically detected and removed. Phase residuals for the flight receiver arc typically about 5 mm RMS; pseudorange residuals arc typically about 70 cm RMS. These values arc roughly equal to the combined instrumental noise and multipath error expected on the two observables, implying no substantial mismodeling in the estimation process. The GPS data arc in general of high quality; onl y ().() 1 % of data arc detected as anomalous and removed from the solut i on,

Orbit overlap. TOPEX/POSEIDON GPS data arc processed in 30-hr arcs centered on noon UTC. This yields adjacent orbits with 6 hrs of overlap. Although the data in the overlap interval arc common to the two arcs, the orbit solutions in the overlap arc only partially correlated because of the largely independent determination of GPS dynamic orbits for each arc. The orbit overlap agreement is therefore a rough but somewhat opt i mi st ic indicator of orbit quality,

To avoid degradation from edge effects (increased error at the ends of the solution arcs resulting from the absence of data on the other side to constrain the stochastic esti mate) encountered with reduced dy nami c solut ions, 45-min segments from each end of the two solutions arc omitted in the RMS comparisons. This corresponds to 3 times the time constant used for the arbitrary 3-D stochastic accelerations. Table 1, summarizes the statistics of the RMS overlaps for the reduced dynamic JGM-2 and JGM-3 orbits.

Table 1. Statistics for RMS Overlaps Differences of Reduced Dynamic TOPEX/POSEIDON Orbits

		Radial (cm)	Cross Track (cm)	Along Track (cm)
JGM-2	**Mean RMS**	1.0	3.3	3.0
125 Overlaps	**Standard Deviation of RMS**	0.44	1.6	1.1
JGM-3	**Mean RMS**	1.1	1.6	2.9
83 Overlaps	Standard Deviation of RMS	0.5	0.7	1.4

Comparison with CSR SLR/DORIS Orbits. The RMS differences between the CSR orbits determined with independent software and data were computed for ten 10-day TOPEX/POSEIDON cycles. Both solutios used JGM-3. The average RMS difference in radial, cross, and along track was 2.0, 8.6, and 6.5 cm. Since these orbits share some of the same dynamic models, some of the errors may be common.

Altimeter Crossovers. A key method for assessing the relative radial accuracy of different orbits relics on altimeter data collected by the spacecraft. TOPEX/POSEIDON carries a radar altimeter that measures the range to the sea surface with an uncertainty of less than 4 cm RMS. These range measurements can be used together with the precise radial orbit solution to determine the geocentric height of the sea surface. At the points in the ocean where the satellite ground tracks intersect on ascending and descending passes, two such determinations of sea height can be made. in the absence of errors in the radial component of the orbit and in the media corrections to the altimeter range, the height difference at the crossing point location is a measure of the true variability of the ocean surface. Thus the standard deviation of the height difference can be written as

$$\sigma^2_{height} = \sigma^2_{ocean} + 2 \times \sigma^2_{radial\ orbit} \tag{2}$$

assuming orbit errors are uncorrelated with the same standard deviation on the ascending and descending arcs. If we have computed the height standard deviation using two different orbit solutions (e.g. GPS and SLR/DORIS) then differencing the corresponding eq. 2's eliminates the ocean variability and yields an equation for the relative accuracy of the two orbits in the radial component.

For eight of the nine 10-day cycles(Fig. *2)*, the JPL reduced dynamic orbits yield smaller crossover variances with a mean for the nine cycles of 2.7 cm^2. This would indicate improved radial orbit accuracy of 1.2 cm.

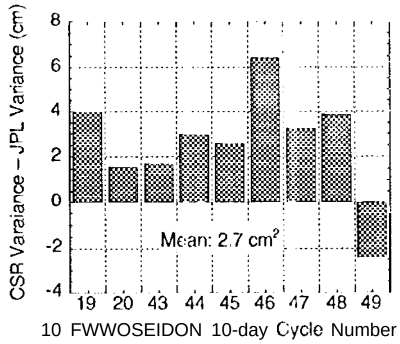

Figure 2. Altimeter Crossover Differences CSR - Reduced Dynamic

4. EUVE Real Time Positioning

Using the single-frequency EUVE data we wish to explore algorithms which could be run in real time on-board a spacecraft to produce the most accurate position. Although the EUVE receiver was the engineering version of the TOPEX/POSEIDON receiver there are several complications compared to TOPEX/POSEIDON. The dual antennas are small patch antennas located on the spacecraft body yielding much higher multipath errors. More seriously, EUVE at 500 km altitude has more ionosphere above it and no dual frequency calibration. Finally, in real time we can not use smoothing in the orbit estimate and must limit the computational complexity of the models for realistic on-board calculations.

To control the ionospheric errors, we investigate the use of the Group and Phase ionospheric {calibration (GRAPHIC) data t ype [Y/reck, 1993]. Since the effect of the ionosphere is to additively increase the observed group delay and to additively decrease the observed delay in phase by the same amount (measured in terms of range), adding the two data types together and dividing by two eliminates the effect of the ionosphere. The GRAPHIC data type is a biased measure of range (biased because the phase is biased) having half the error of pseudorange (since pseudorange noise is large compared to phase), but no ionospheric error.

To reduce the computational complexity, we investigate simplifications of the dynamic model. Simple numerical integrators can be used on-board to integrate the equations of motion. The computational cost is dominated by the size of the gravitational field used in the force modeling. Computation may be significantly reduced by judiciously selecting terms from the spherical harmonic representation of the best available gravitational models.

4.1 EUVE Definitive Truth Solution

Truth solutions are generated with the full dynamic mode] and reduced dynamics using GRAPHIC data from EUVE and dual frequency data from the ground network. Models include a 70X70 gravity field, atmosphere drag models, and more complete box-wing models for the spacecraft ori ent at ion and physical parameters. The weaker single-frequency EUVE data do not contribute to improving the GPS orbits over the high precision processing done routinely with ground data at J])], [*Zumberge et al.*, 1995]. Thus, unlike TOPEX/POSEIDON, the GPS orbit solutions and station coordinates arc held fixed. White noise offsets from a ground station refe) ence clock arc estimated for each satellite and receiver clock in the network. EUVE position, velocit y, drag coefficient, and constant and once.-pcr-rcv empirical accelerat i o) is are esti mated, and solutions arc iterated until these parameters converge. After convergence, the values of these parameters arc held fixed, and a final reduced dynamic step is performed, Orbit overlap tests indicate that the truth orbits are accurate to about 1 meter (3D RMS), with the along track component the least well determined [*Gold et al.,* 1994].

4.2 Real Time Performance

Processing Scenario. Wc limit the discussion to reduced dynamic solutions using GRAPHIC data. For comparisons to other data types and algorithms scc *Gold et al.* , 1994. The reduced dynamic technique must be modified slightly for the real time application since a converged smoothed dynamic solution is unavailable in real time. For real time reduced dynamics, wc start with an aprio) i ephemeris for EUVE that is good to ***75-100 m,*** easily obtainable from a fcw point position solutions on-board or uploaded the ground. Broadcast clocks and a good approximation to the broadcast ephemeris arc used for GPS. The combination of less precise dynamic models and n o smoothing require much larger stochastic corrections. Values of from 20,000--300 nm/sec^2 with a 15 min time correlation were found to be optimal depending on the data and the force model. Data arc processed in 30-hr arcs and compared to the truth solution over the last 27-hrs to allow for filter convergence. Terms from the 50x5()

JGM-2 gravity field are selected based on a linear perturbation analysis [*Rosborough et al.*, 1 987].

Results. in Table 2, the first row gives the size of the perturbations to be studied with the linear analysis. The second row lists the number of terms that are needed from the JGM-2 gravity field such that all the other terms will contribute less than the number listed in the first row. Rows 3 and 4 show the performance, with and without SA, of the real-time reduced dynamic solution (3D RMS for 27-hrs). The final two rows show the level of stochastic acceleration necessary to achieve the best orbit with the selected gravity field. Note that dynamics smooth out much of the SA error.

Table 2. JGM-2 Gravity Field Selection vs. Real Time Orbit Performance

Perturbation	> 10 m	> 4 m	>2.5 m	> 1 m	> 0.5 m	> 0.3 m	Full Field
# of Terms	78	117	157	282	416	554	2597
SA RMS	47.2 m	35.0 m	31.8 m	22.6 m	19.3 m	17.5 m	13.8 m
no-SA RMS	31.0 m	25.5 m	23.5 m	19.2—m	16.7 m	15,9 m	11.8 m
SA. Accel. nm/sec²	20000	1000	800	500	400	400	300
no-SA Accel. nm/see?	10000	3000	2000	1000	600	600	400

5. Conclusions

Data from two GPS flight receivers were processed. With the dual frequency TOPEX/POSEIDON receiver RM S accuracies of approximatel y 2 cm in the radial and 5 cm in cross and along track components are obtainable. Evidence supporting this level of accuracy includes orbit overlaps with an RMS of 1.1, 1.6, and 2..9 cm in the radial, cross, and along track components; anti comparison with orbits determined with SLR/DORIS data and independent software with an RMS agreement of 2.0, 8.6 and 6.5 cm (radial, cross and along track). Further tests using altimetry data, which is independent of the orbit determination process, show that the GPS orbit is of higher accuracy than the SLR/DORIS determined orbit.

For EUVE real time RMS positioning accuracies in 3D of 15 m are possible with a single-frequency receiver in the presence of' SA. For real time positioning it is important to control the computational complexity of the cm-board algorithm. The numerics] integrator for EUVE was simplified by a Judicious choice of the components of the gravity field model. The 15 m accuracy was validated by comparison to a post-processed orbit with an RMS accuracy of about 1 m RMS.

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References

Bertiger, Winy 1. and Catherine 1.. Thornton, "GPS-Based System for Satellite Tracking and Geodesy," *Navigation: Journal of the Institute of Navigation,* Vol. 36, No. 1, Spring 1989, pp. 99-113.

Bertiger, W. 1., Y. E. Ilar-Sever, E. J. Christensen, E. S. Davis, J. R. Guinn, B. J. Haines, R. W. Ibanez-Meier, J. R. Jee, S. M. Lichten, W. G. Melbourne, R. J. Muellerschoen, T. N. Munson, Y. Vigue, S. C. Wu, and T. P. Yunck, B. E. Schutz, 1'. A. M. Abusali, H. J. Rim, M, M. Watkins, and P. Willis, "GPS Precise Track i ng Of Topex/Poseidon: Results and implications," *JGR Oceans Topex/Poseidon Special issue,* Vol. 99, No. C12, Dec. 1995.

Bowyer, Stuart, "Extreme Ultraviolet Astronomy," *Sci. Am.,* Vol. 271, No. .2, p.32 Aug. 1, 1994.

Gold, Kenn, Angie Reichert, Winy Bertiger, Sien Wu, and Tom Yunck, "A Study of Real Time and Post Processed GPS Orbit Determination under Selective Availability for the Extreme Ultraviolet Explorer," proceedings of ION GPS-94, Salt Lake City, UT, September 20-23, 1994.

Gold, Kenn 1.., "GPS Orbit Determination for The Extreme Ultraviolet Explorer," Ph.D. Dissertation, University of Colorado, Boulder, CO, 1994.

Gold, Kenn, Winy Bertiger, Sien Wu, Tom Yunck, "GPS Orbit Determination for the Extreme Ultraviolet Explorer", *Navigation: Journal of the Institute of Navigation,* Vol. 41, No. 3, Fall 1994, pp. 337-351.

Melbourne, W. G., E. S. Davis, T. P. Yunck and B. D. Tapley, The GPS Flight Experiment on TOPEX/POSEIDON, *Geophys. Res. Lett., 21*(19), 2171-2174, 1994.

Nerem, ***R. S.,*** et al., Gravity model development for TOPEX/POSEIDON: Joint gravity models 1 and 2, *JGR Oceans Topex/Poseidon Special Issue*, Vol. 99, No. Cl 2, Dec. 1995.

Rosborough, G. W., Tapley, B. D., "Radial Transverse and Normal Satellite Position Perturbations Due to the Geopotential," *Celestial Mechanics,* Vol. 40, pp. 409-421, 1987.

Tapley, B. D., M. M. Watkins, J. C. Ries, G. W. Davis, R. J. Eanes, S. R. Poole, H. J. Rim, B. E. Schutz, C. K. Shum, R. S. Nerem, F. Lerch, E. C. Pavlis, S. M. Klosko, N. Pavlis, and R. Williamson, "The JGM-3 Gravity Model, presented at the XIX General Assembly of the European Geophysical Society," Grenoble, France, April 25-29, 1994.

Tapley, B., et al., "Precision orbit determination for TOPEX/POSEIDON," *JGR Oceans Topex/Poseidon Special Issue*, Vol. ***99, No.*** Cl ***2, Dec. 1994.***

Webb, F. H., and J. F. Zumberge (Eds.), *An introduction to GIPSY/OASIS II, JPL Internal Document D-11088*, Jet Propuls. Lab., Pasadena, Calif., July, 1993.

Wu, S. C., Y. Bar-Sever, S. Bassiri, W. I. Bertiger, G. A. Hajj, S. M. Lichten, R. P. Malla, B. K. Trinkle and J. T. Wu, Topex/poseidon Project: Global Positioning System (GPS) Precision orbit Determination (POD) Software Design, Rep. JPL Internal Document D-7275, Jet Propuls. lab., Pasadena, Calif., March 1990.

Yunck, T. P., "Coping with the Atmosphere and Ionosphere in Precise Satellite and Ground Positioning", in *Environmental Effects on Spacecraft Trajectories and Positioning*, A. Vallance-Jones, ed., AGU Monograph, 1993.

Yunck, T. P., S. C. Wu, J. T. Wu, C. L. Thornton, Precise tracking of remote sensing satellites with the Global Positioning System, *IEEE Trans Geosci Rem Sens* (28), Jan 1990.

Zumberge, J. F., and W. I. Bertiger, Vol. 1, Chapter 16, *The Global Positioning System – Theory and Application,* Senior Editors: B. W. Parkinson, J. J. Spilker, Jr.; Editors: P. Axelrad, P. Enge., AIAA, in press 1995.